CONDUCTIVITY OF EXPLOSIVELY SHOCKED POTASSIUM CHLORIDE

S.I. Shkuratov[1ξ], J. Baird[1], V.G. Antipov[1], E.F. Talantsev[2], L.L. Altgilbers[3]
[1]Loki Incorporated, Rolla, MO 65409, U.S.A.
[2]Pulsed Power LLC, Lubbock, TX 79416, U.S.A.
[3]U.S. Army Space and Missile Defense Command/Army Strategic Command, Huntsville, AL 35807, U.S.A.

Abstract

Results of experimental investigations of the electrical conductivity of explosively shocked polycrystalline and single crystal potassium chloride samples are presented. KCl polycrystalline samples (diameter D = 33.0 mm and thickness h = 10.0 mm) and KCl single crystals oriented in the <100> direction (D = 38.0 mm and h = 6.0 mm) were loaded by shock waves generated from high explosives. It follows from the experimental results that the resistance of KCl single crystals is reduced to 10^{-4} Ω·cm due to the explosive shock compression.

I. INTRODUCTION

The operation of classical magnetic flux compression generators (FCGs) is based on the compression of magnetic flux by explosively expanding metallic armatures inside the stators of the FCGs [1]. Different approaches to magnetic flux compression have been under discussion since the beginning of the 1980s [2,3]. It was experimentally demonstrated that compression of aluminum or silicon powder by a closed systems of shock waves lead to magnetic flux compression in the system [2,3].

Another approach to magnetic flux compression without an expanding or moving metallic armature in the system is to utilize the shock-induced dielectric-metallic state phase transition in solid dielectrics. For this approach it is important to search for dielectric materials that are capable of changing their conductivities due to shock compression.

Group of solid dielectrics named "ionic crystals" (NaCl, KCl, KBr, KI, CsI, etc.) possess the unique ability to emit electrons under mechanical stress [4]. There is a possibility that these materials could provide high electrical conductivity under shock compression.

Shock-induced dielectric-metallic state phase transition in potassium chloride has been under investigation from the early 1960s to the present time [5-10]. Detailed investigations of the conductivity of KCl polycrystalline and single crystal samples mechanically loaded by plane shock waves generated by a pellet accelerated by high explosives and in a light gas gun were performed in [6, 7, 10]. In these works, it was demonstrated that KCl samples pass through the dielectric-to-conductive state transition at shock wave pressures exceeding 15 GPa [6, 7, 10].

We performed experimental investigations of the conductivity of KCl polycrystalline and single crystal samples shocked directly by high explosives.

II. RESULTS AND DISCUSSION

Figure 1 shows a schematic diagram of the experimental device we developed for investigation of the dielectric-metallic state phase transition in explosively shocked solid dielectrics. The device contains an explosive chamber and the plastic holder with the investigated dielectric sample. The high explosives were in direct contact with the target. The solid dielectric sample was encapsulated with polyurethane compound inside the holder to avoid the effect of explosive plasma on the recorded signals.

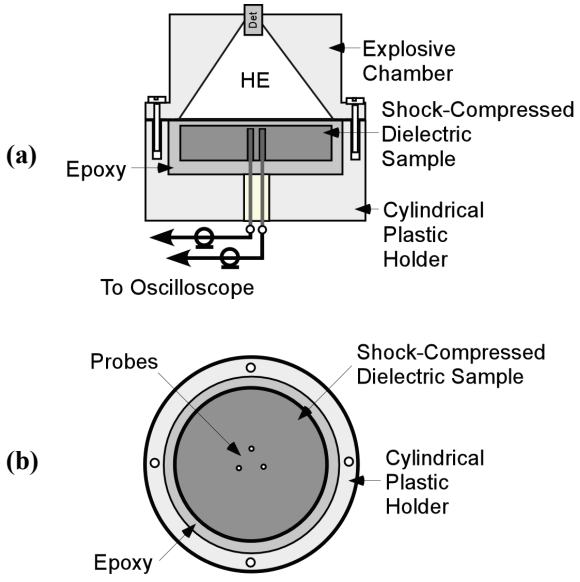


Figure 1. Schematic diagram of the device developed for investigation of the shock-induced dielectric-metallic state phase transition in solid dielectrics. (a) – cut-away view of the device. (b) – top view of the sample holder.

ξ E-mail: shkuratov@lokiconsult.com

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2009	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Conductivity Of Explosively Shocked Potassium Chloride	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Space and Missile Defense Command, Huntsville, AL 35807, U.S.A.**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
Results of experimental investigations of the electrical conductivity of explosively shocked polycrystalline and single crystal potassium chloride samples are presented. KCl polycrystalline samples (diameter D = 33.0 mm and thickness h = 10.0 mm) and KCl single crystals oriented in the <100> direction (D = 38.0 mm and h = 6.0 mm) were loaded by shock waves generated from high explosives. It follows from the experimental results that the resistance of KCl single crystals is reduced to 10-4 Ù·cm due to the explosive shock compression.

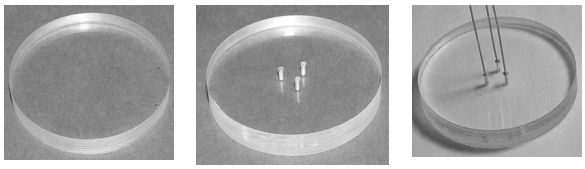
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**5**	

We performed experiments with potassium chloride samples of two types. The KCl samples of the first type were prepared with fine KCl powder (spectroscopy grade/ultra-pure, supplied by Alfa Aesar). We pressed the KCl powder into tablets of 33.0 mm diameter (D) and 10.0 mm thickness (h). The density of the polycrystalline samples after pressing was 97.8% of the solid state density.

The KCl samples of the second type were single crystals of D = 38.0 mm/h = 6.0 mm (supplied by Alfa Aesar), with crystallographic orientation of <100>. Photographs of a typical single crystal KCl samples are shown in Fig. 2.

Three probe holes were drilled in the central part of KCl samples of both types. The distance between the centers of the holes was 5.0 mm, and the hole diameters was 1.0 mm. The distance between the surface of the sample facing the high explosive charge and the bottom of the probe holes was 0.3 mm.



(a) **(b)** **(c)**

Figure 2. KCl single crystal of D = 38.0 mm/h = 6.0 mm. (a) – the initial single crystal. (b) – the single crystal with drilled probe holes. (c) – the single crystal with three metallic probes embedded in the holes.

Metallic probes were made of 0.5 mm diameter Inconel wire. Before embedding the metallic probes into the KCl samples, the holes were filled with pure indium (melting temperature 190 C). The Inconel probes were then embedded in the melted indium; a series of photographs illustrating this process is in Fig. 2. After installation of the metallic probes, we placed the KCl samples in the polycarbonate holders and encapsulated the samples with a polyurethane compound.

Several experimental techniques were developed for investigations of the shock-induced dielectric-metallic state phase transition in dielectrics. In our work we used the technique developed in [11-12], which differentiates the signal generated due to the appearance of electrical conductivity in the shocked dielectric sample from the signal generated due to the polarization of shock-compressed material. This technique was developed in [11-12] for measurement of the conductivity of shock-compressed dielectric liquids. It was successfully used for measurement of the conductivity of shock-compressed solid dielectrics [10].

A schematic diagram of our experimental setup is shown in Fig. 3. It contains the dielectric sample, with probes imbedded in the body of the sample, and the differential circuit. The probes are placed inside the sample normal to the propagation direction of the shock wave front.

Before the beginning of the experiment, capacitors C_1 and C_2 are charged to 90 V from electrochemical cells (Fig. 3). The charging path is B1-E-D-C1 for capacitor C_1 and B2-E-D-C2 for capacitor C_2.

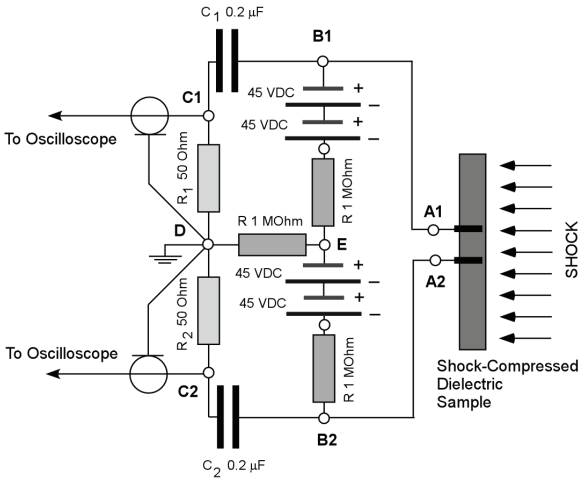


Figure 3. Schematic diagram of the experimental setup used for investigations of shock-induced dielectric-metallic state phase transition.

Probe A1 is connected to the positive plate of capacitor C_1. Probe A2 is connected to the negative plate of capacitor C_2. Probe A3 (not shown in Fig. 3) is connected directly to the input of an oscilloscope.

Before shock compression of the dielectric sample, the electrical connection between probes A1 and A2 is broken. The capacitors remain fully charged because of the broken discharge path B1-A1-A2-B2-C2-D-C1.

When the shock front propagates through the dielectric sample it causes two processes. It initiates electrical conductivity in the dielectric material, and shock compression induces polarization of the dielectric sample. This polarization voltage is applied to probes A1, A2 and A3.

When shock-induced conductivity appears in the sample, probes A1 and A2 become electrically connected. The positive plate of capacitor C_1 becomes connected to the negative plate of capacitor C_2 through the conductive media between probes A1 and A2. The capacitors start discharging. The discharge current flows in the circuit: B1-A1-A2-B2-C2-D-C1 (Fig. 3).

Points C1 and C2 are connected to the inputs of the same digital oscilloscope. Point D is grounded (Fig. 3). Two voltage pulses are generated due to the discharging of the capacitors C_1 and C_2 through the shocked dielectric sample. The waveform of the first pulse contains a time history of the negative voltage drop across resistor R_1 (due to the flow of the discharging current in the circuit), plus the dynamics of the voltage induced in probe A1 due to the polarization of the sample by a shock wave. The

waveform of the second pulse contains a time history of the positive voltage drop across resistor R_2 (due to the flow of the discharging current in the circuit), plus the dynamics of the voltage induced in probe A2 due to the polarization of the sample by a shock wave.

Probe A3 is connected directly to the oscilloscope. The waveform of the signal recorded from this probe contains a time history of the voltage generated due to the shock polarization of the dielectric sample.

(a) **(b)**

Figure 4. (a) – top view of the polycarbonate holder containing KCl polycrystalline sample. (b) – the experimental device loaded with a high explosive charge and prepared for explosive test.

To obtain the dynamics of the changing resistance of the shocked dielectric sample without the shock polarization effect, we have to perform the real time point-to-point subtraction of two waveforms and divide the result by factor of two.

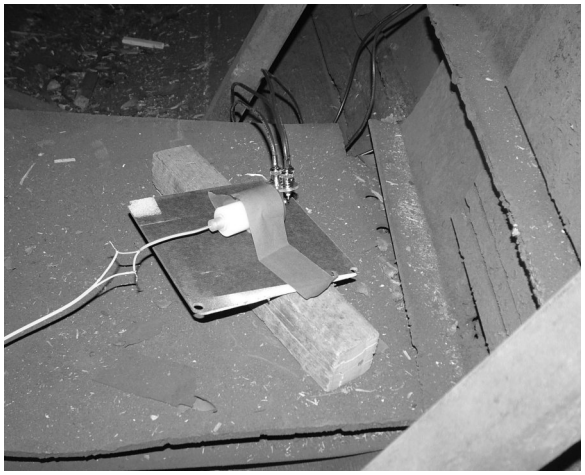


Figure 5. The experimental device containing a KCl sample placed in the detonation tank. Three coaxial 50-Ω signal cables connect three metallic probes embedded in the sample to the external measuring and recording system.

We performed the first series of explosive tests with KCl polycrystalline samples. Figs. 4 and 5 present stages of preparation of one of the explosive experiments. The mass of high explosive charge in these experiments was 24.9 g of C-4 high explosives (Chapman-Jouguet state pressure of 22.36 GPa). A single RP-501 explosive-bridge-wire RISI detonator was used to initiate each experimental device.

Two of the three metallic probes embedded in the KCl sample were connected to the inputs of the differential circuit (Figs. 3). Two outputs of the circuit were connected to a digital Tektronix TDS6604 oscilloscope (6 GHz bandwidth/sample rate 20 GS/s). The time resolution in these experiments was 0.4 ns.

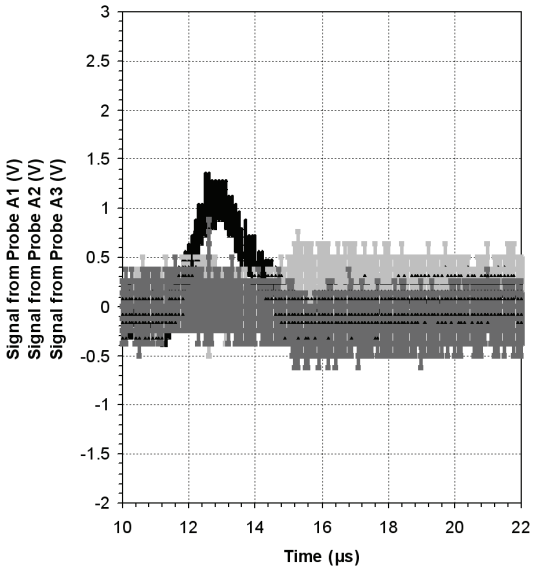


Figure 6. A typical waveform of the signals recorded in the explosive tests with KCl polycrystalline samples. Output 1 of the differential circuit (light gray). Output 2 of the differential circuit (dark gray). The probe (A3) connected directly to the oscilloscope (black).

Figure 6 shows typical waveforms recorded from three probes embedded in the KCl polycrystalline sample. The amplitude of the polarization voltage recorded from Probe A3 connected directly to the oscilloscope is 1.3 V (black waveform in Fig. 6). There are no signals from both outputs of the differential circuit, i.e. Probes A1 and A2 (light and dark gray in Fig. 6). The discharge of the capacitors of the differential circuit did not happen, so it is obvious that we did not detect observable conductivity in shock compressed KCl polycrystalline samples.

We performed the second series of explosive experiments with KCl single crystals of D = 38.0 mm/h = 6.0 mm. The design of the experimental device and experimental setup in these tests were identical to those in tests with polycrystalline KCl samples described above. The mass of high explosive charge in these experiments was 43.8 g of C-4 high explosives with one RP-501 detonator.

Figure 7 shows typical waveforms recorded from three probes embedded in the KCl single crystal. The signals recorded from the differential circuit (light and dark gray

waveforms) reached +29.0 V and -31.6 V, which corresponds to significant electrical conductivity of the shock-compressed KCl single crystal. The amplitude of the polarization voltage recorded from Probe A3 connected directly to the oscilloscope was 5.1 V (black waveform in Fig. 7).

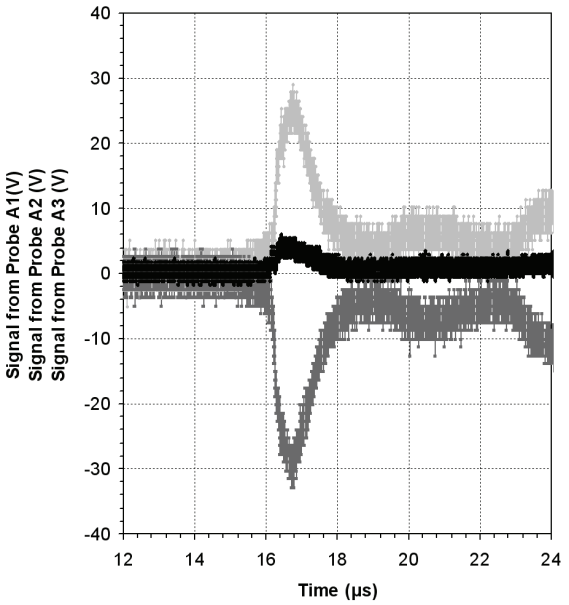


Figure 7. A typical waveform of the signals recorded in the explosive tests with a KCl single crystal sample. Output 1 of the differential circuit corresponds to Probe A1 (light gray). Output 2 of the differential circuit corresponds to Probe A2 (dark gray). Probe A3 was connected directly to the oscilloscope (black).

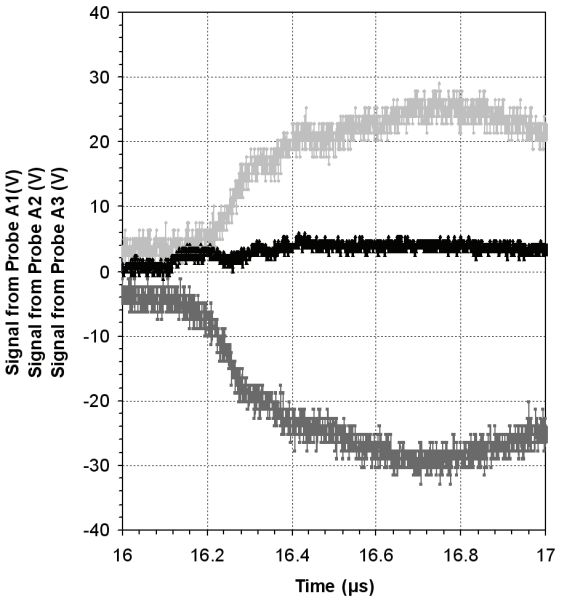


Figure 8. Waveforms shown in Fig. 7 in a magnified time scale.

Figure 8 shows the signals from Fig. 7 in a magnified time scale. The risetime (0.1 to 0.9) of the signals recorded from the differential circuit was about 500 ns.

Figure 9 shows the waveform obtained as a result of point-to-point subtraction of two waveforms recorded from outputs of the differential circuit. The result of the subtraction was divided by a factor of 2. The amplitude of the signal was 29.1 V.

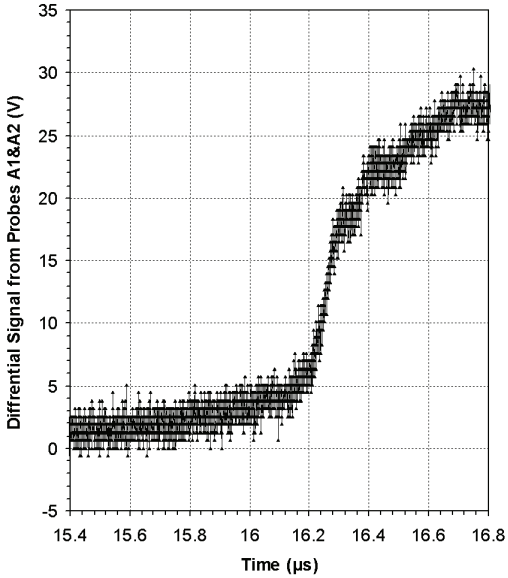


Figure 9. The waveform obtained by a point-to-point subtraction of two waveforms recorded from outputs of the differential circuit. The result of subtraction was divided by a factor of 2.

In accordance with our estimations based on the calibration of the differential circuit (Fig. 3), the resistance of explosively shocked KCl single crystal (Fig. 9) ranges from 10^{-4} to $5 \cdot 10^{-4}$ Ω·cm.

III. SUMMARY

The dielectric-metallic state phase transition in explosively shocked (Chapman-Jouguet state pressure of 22.36 GPa) single crystals was experimentally detected.

It is possible that we did not detected observable conductivity in our experiments with KCl polycrystalline samples because of their relatively low (97.8% of solid state) density.

IV. REFERENCES

[1] L.L. Altgilbers, J. Baird, B. Freeman, C.S. Lynch, and S.I. Shkuratov, Explosive Pulsed Power. Imperial College Press, London, 2009.

[2] E.I. Bichenkov, S.D. Gilev, A.M. Trubachev. "MC-generators utilizing the transition of the semiconductor to conducting state". J. of Applied Mechanics and Technical Physics, Vol. 5, 1980, pp.125-129 (in Russian).

[3] K. Nagayama. “New Method of Magnetic Flux Compression by Means of the Propagation of Shock Induced Metallic Transition in Semiconductor”, Appl. Phys. Letters, Vol. 38(2), 1981, pp. 109-116.
[4] A. Pierszkala and M. Pirog, “Electrical-Charge and Exoemission Study of Some Ionic Crystals During Plastic Deformation”, Japanese Journal of Applied Physics, vol. 24, Supplement 24-4, pp. 206-208, 1985.
[5] L.V. Altshuler, L.V. Kuleshova, and M.N. Pavlovskii, Sov. Phys. JETP, vol. 12, pp. 10-15, 1961.
[6] K L.V. Kuleshova, Sov. Phys. Solid State, vol. 11, pp. 886-891, 1969.
[7] K L.V. Kuleshova, Phys. Solid Earth, vol. 11, pp. 693-695, 1975.
[8] K L.V. Kuleshova and Pavlovskii, Sov. Phys. Solid State, vol. 18, pp. 332-335, 1976.
[9] K L.V. Kuleshova and Pavlovskii, J. Appl. Mech. Tech. Phys., vol. 18, pp. 689-692, 1977.
[10] N.K. Bourne, D. Townsend, M. Braithwaite, “On Conductivity Changes in Shocked Potassium Chloride”, J. Appl. Phys., vol. 97, 123506, 2005.
[11] S.T. Weir, W.J. Nellis, and A.C. Mitchell, “Electrical Conductivity of Hydrogen Shocked to Megabar Pressures”, in High Pressure Science and Technology 1993, edited by S.C. Schmidt, J.W. Shaner , G.A. Samara, and M. Riss, AIP Conf. Proc. No. 309, (AIP, New York, 1994), pp. 881-883.
[12] W.J. Nellis, S.T. Weir, and A.C. Mitchell, “Minimum Metallic Conductivity of Fluid Hydrogen at 140 GPa (1.4 Mbar)”, J. Appl. Phys., vol. 59, no. 5, pp. 3434-3449, 1999.